



Nacelle lidar calibration – how we do it at DTU Wind Energy

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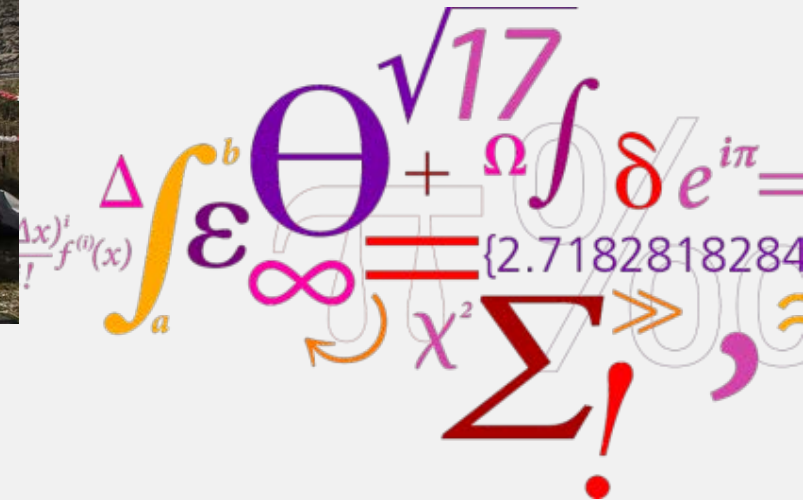
Nacelle lidar calibration – how we do it at DTU Wind Energy



A. Borraccino

IEA Wind task 32 – workshop nacelle lidars
27th September 2017

DTU Wind Energy
Department of Wind Energy



Calibration: why? what?

- Why?

Traceability to SI

Uncertainty quantification

“measurement values are meaningless without their associated uncertainty. The true value is unknowable”

- **Metrology** (= science of measurements)

international standards: JCGM (BIPM, IEC, ISO, etc)

- VIM: international vocabulary of metrology
- GUM: guide to uncertainty in measurements



- **Calibration =**

operation providing as an end-result

- a relation between measured values and reference ones (mathematical model, curve, table, etc)
- associated measurement uncertainties
- a correction of the indicated quantity value

DTU's experience

- **Since 2012:**

Courtney M.: "Calibrating nacelle lidars", [2013], DTU Wind Energy E-0020(EN)

→ original procedures for two-beam nacelle lidars

- **Calibrations of:
(white-box methodology)**



2-beam



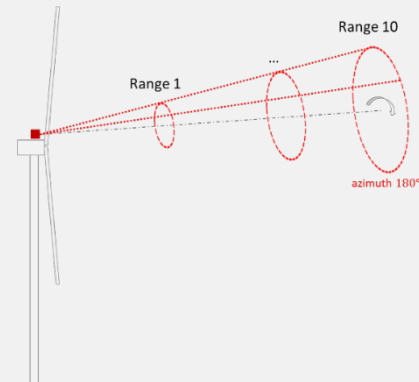
4-beam

Wind Iris

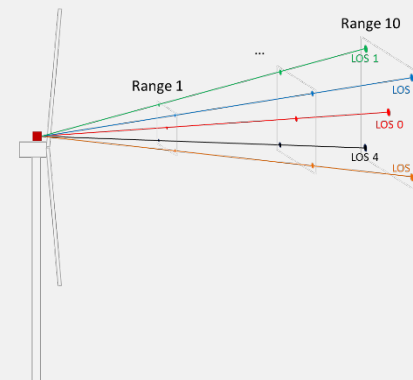
- **Testing of:**



Wind Eye
(2-beam)



ZephIR Dual Mode (ZDM)
continuous wave, conically scanning



**Avent 5-beam Demonstrator
(5B-Demo):** pulsed, step-staring



Calibration of wind lidars: white-box methodology

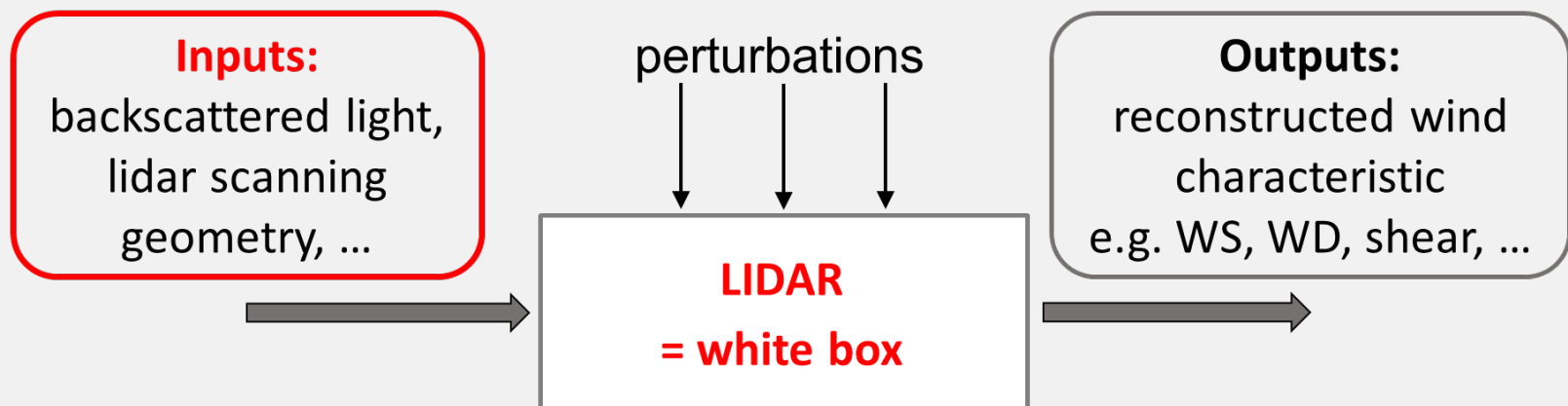
• White-box

– calibration of all the inputs of the Wind Field Reconstruction PROS

- Low sensitivity to WFR assumptions
- Genericity
- Uncertainties on any wind characteristics (WFC)

CONS

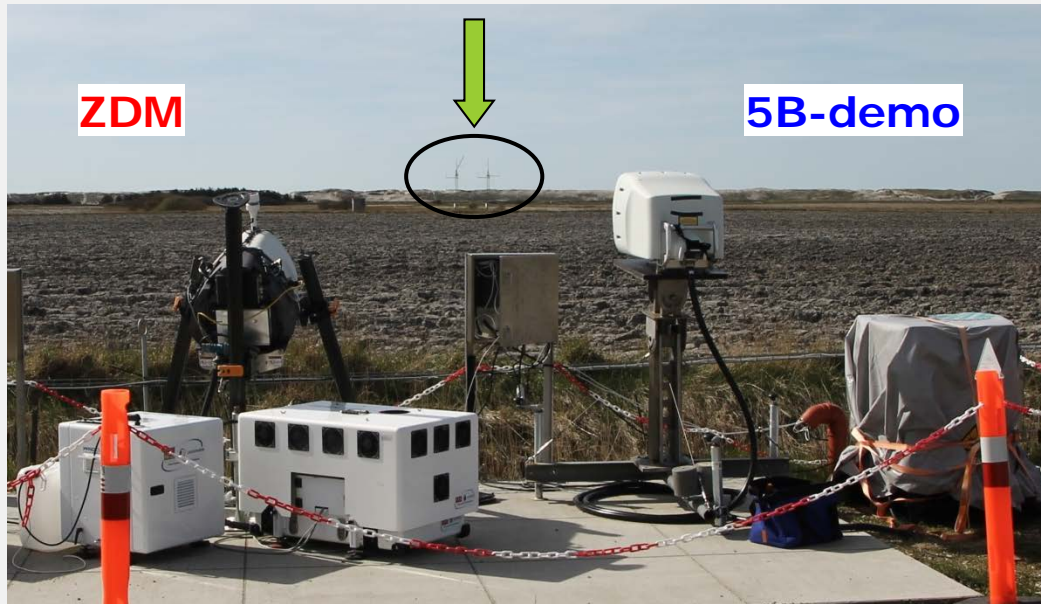
- Longer process
- Need expert knowledge



Generic calibration methodology

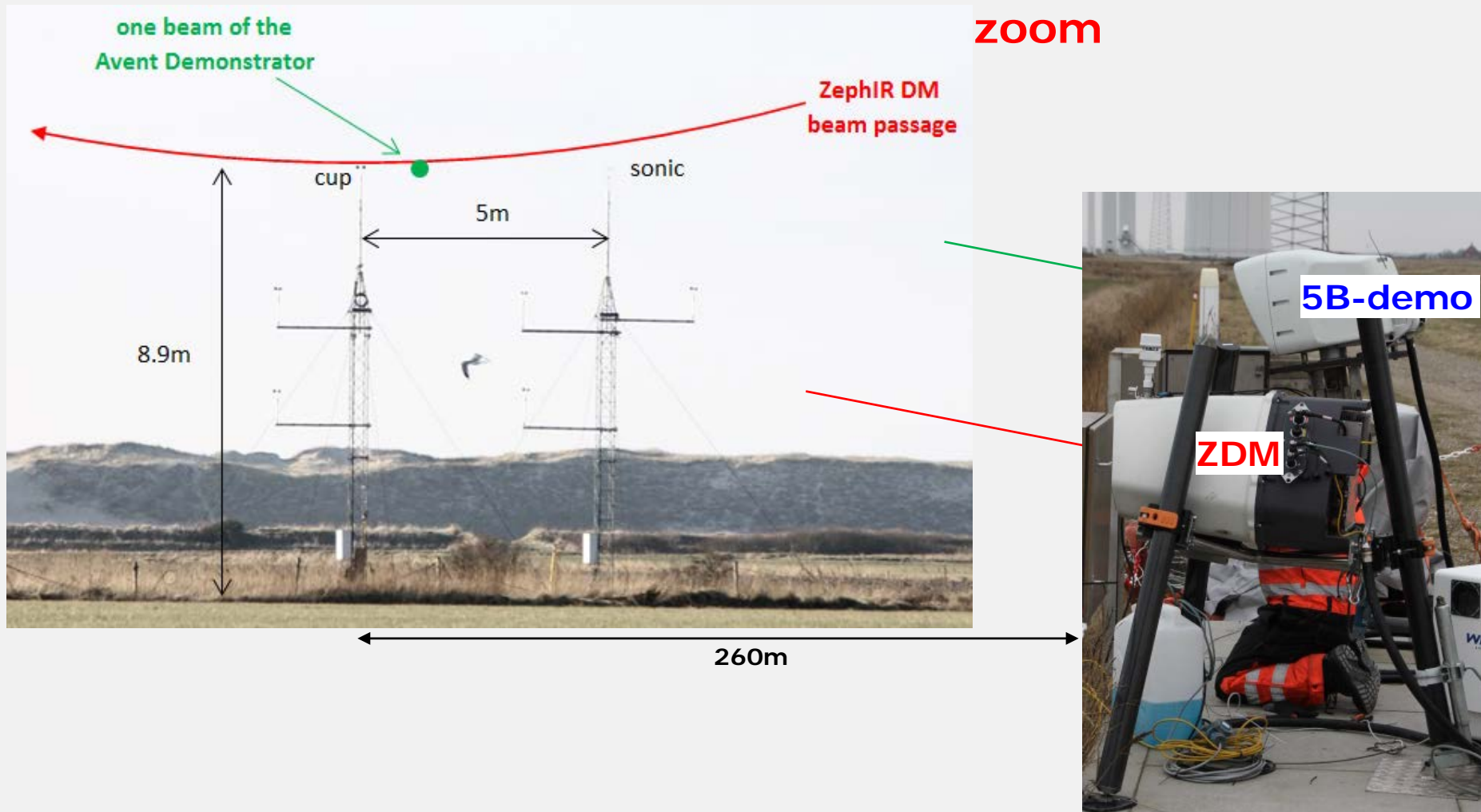
2) calibration of LOS velocity

- Measurement setup, in Høvsøre (DK)



Generic calibration methodology

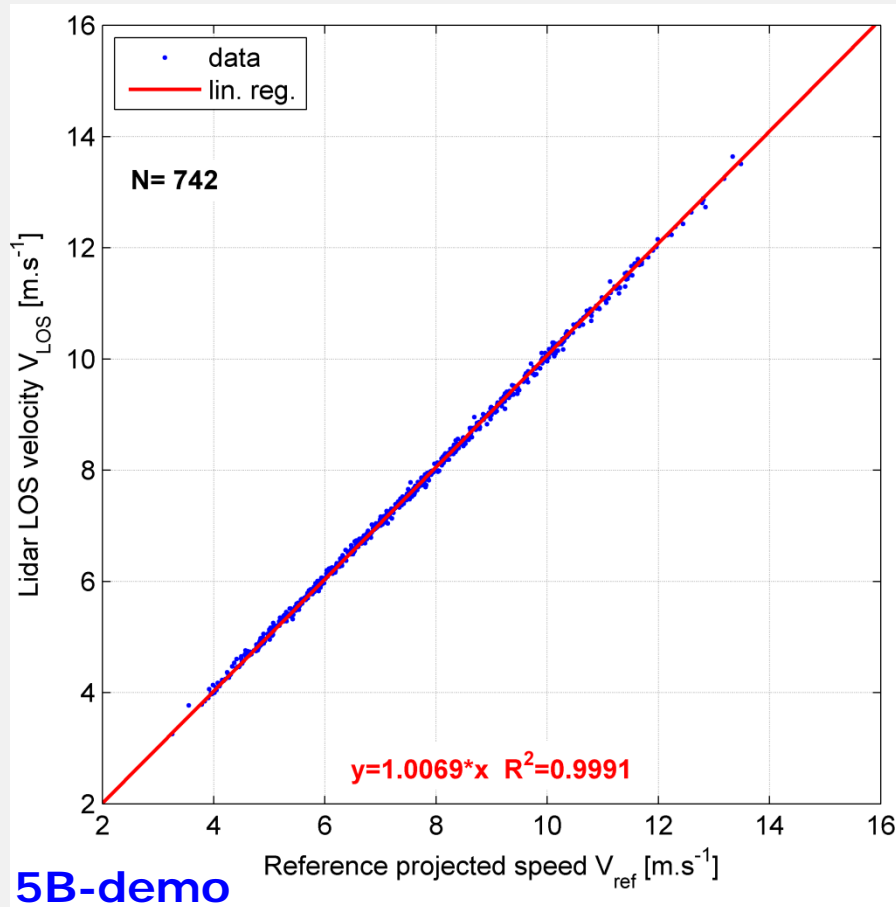
2) calibration of LOS velocity



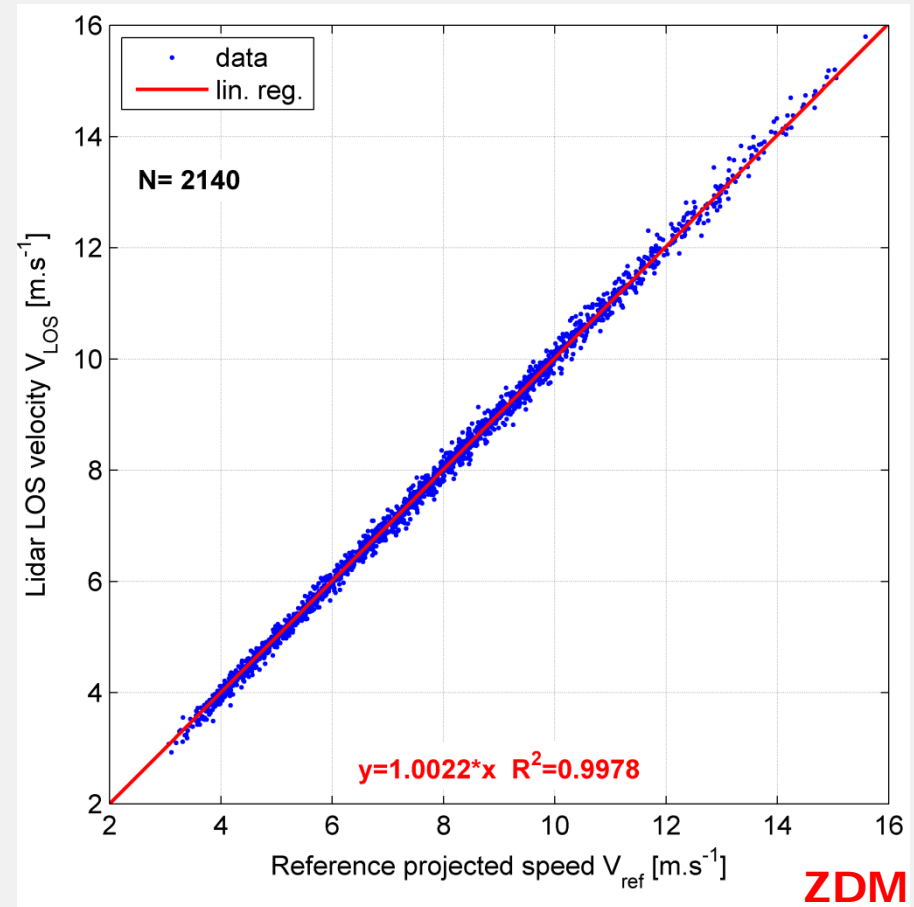
2) Calibration of LOS velocity

Results (1/2)

Linear regressions on 10-min data



LOS 0

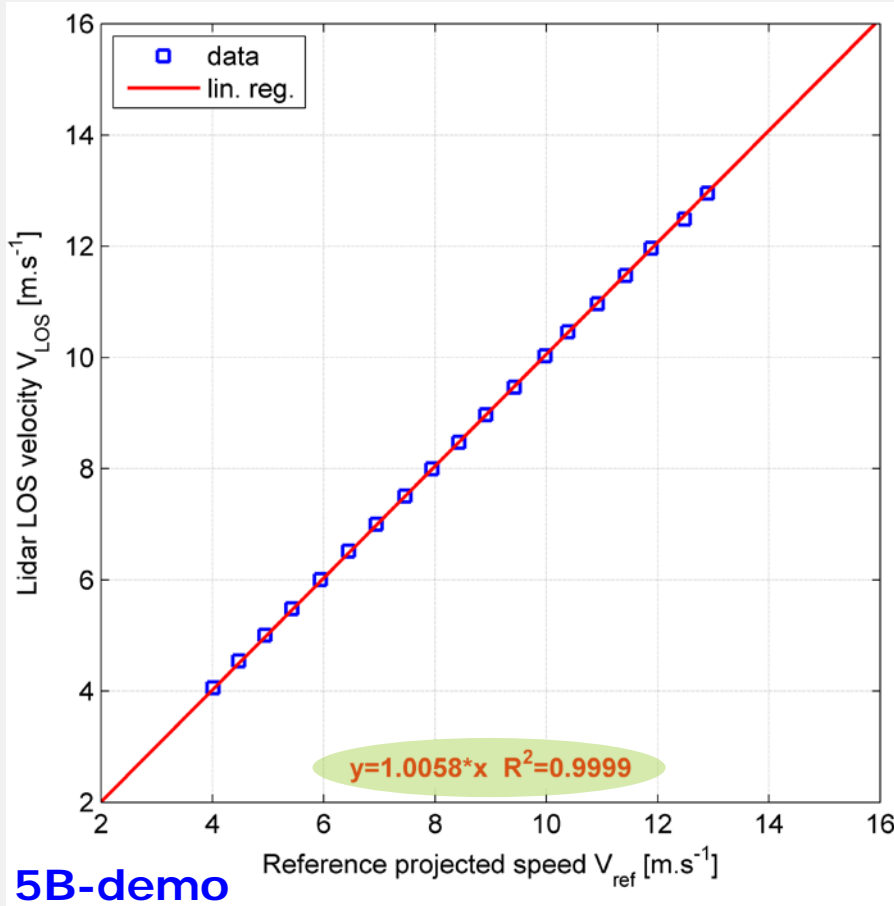


Bottom LOS

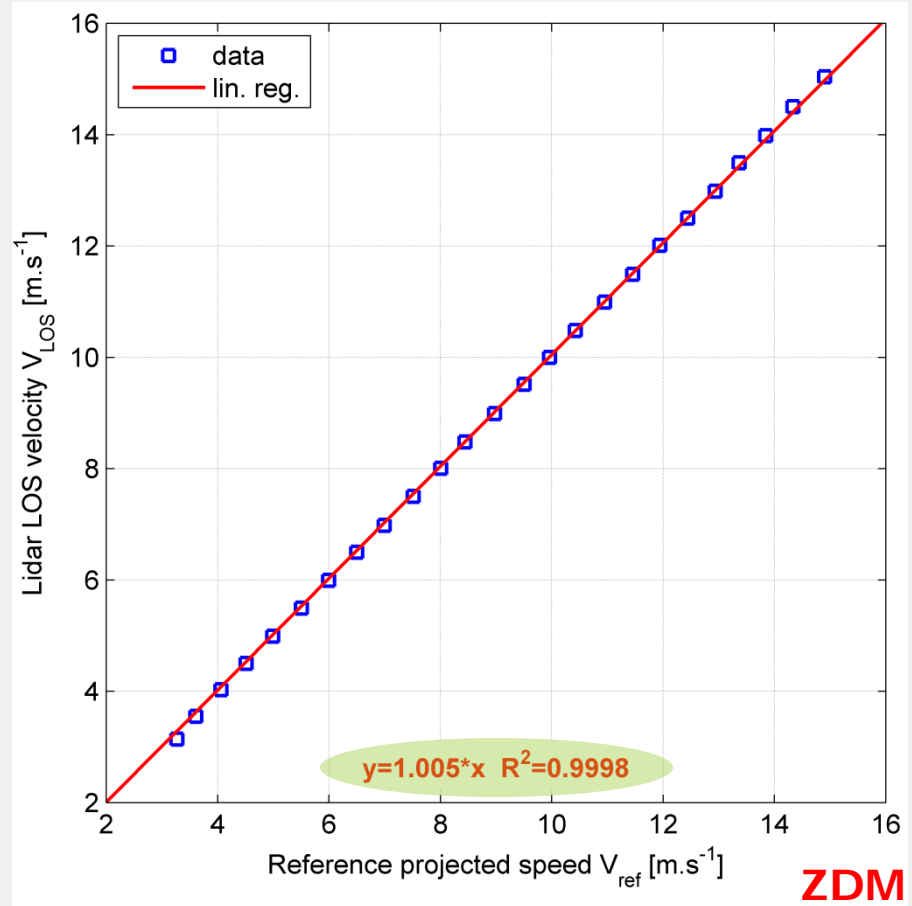
2) Calibration of LOS velocity

Results (2/2)

Linear regressions on binned data



LOS 0



Bottom LOS

→ the calibration relation is obtained!

Uncertainty of LOS velocity

Results

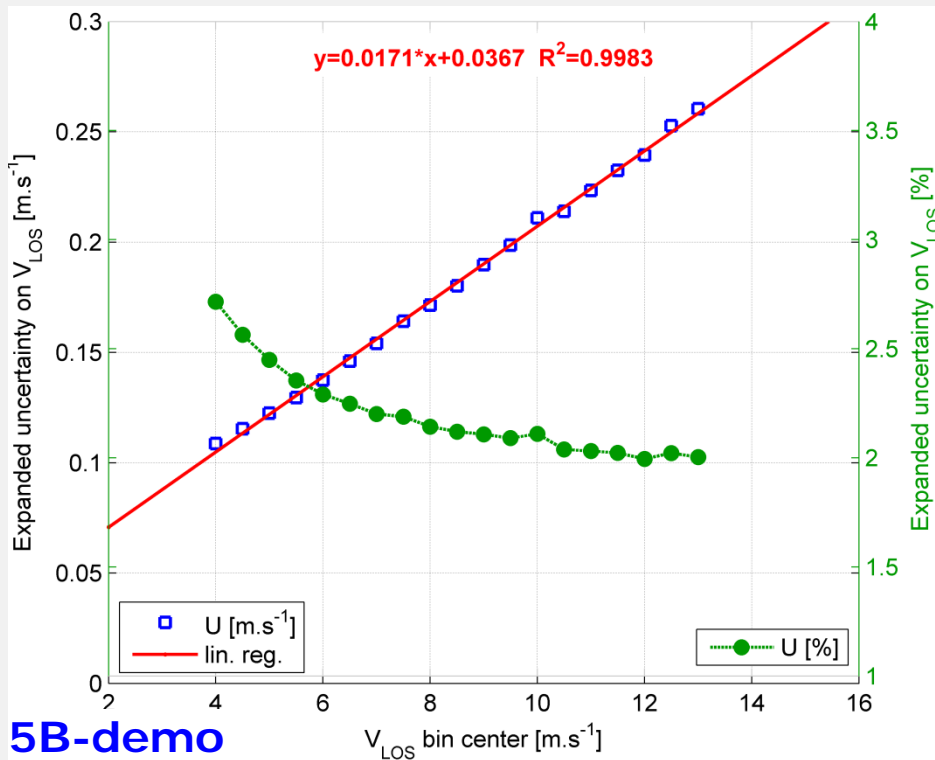
- Expanded uncertainties ($k=2$) vs. V_{los} : in m/s and in %

U_{exp} increases linearly (m/s)

~ 3% at 4m/s

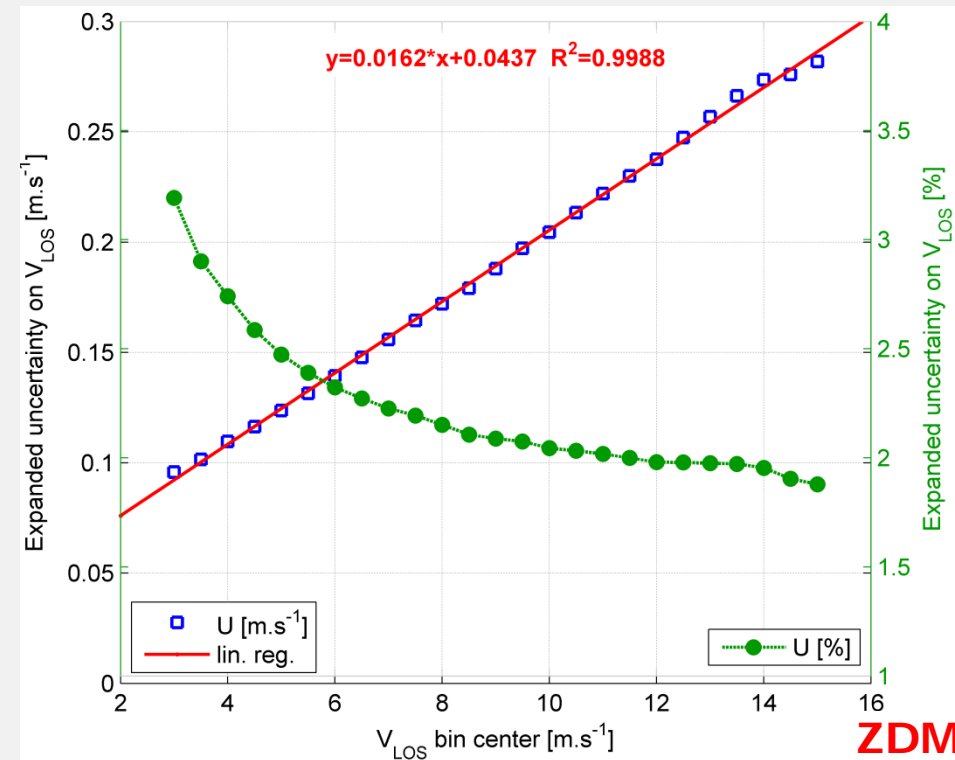
~ 2% at 10 m/s

almost same as cup anemometer



5B-demo

LOS 0



ZDM

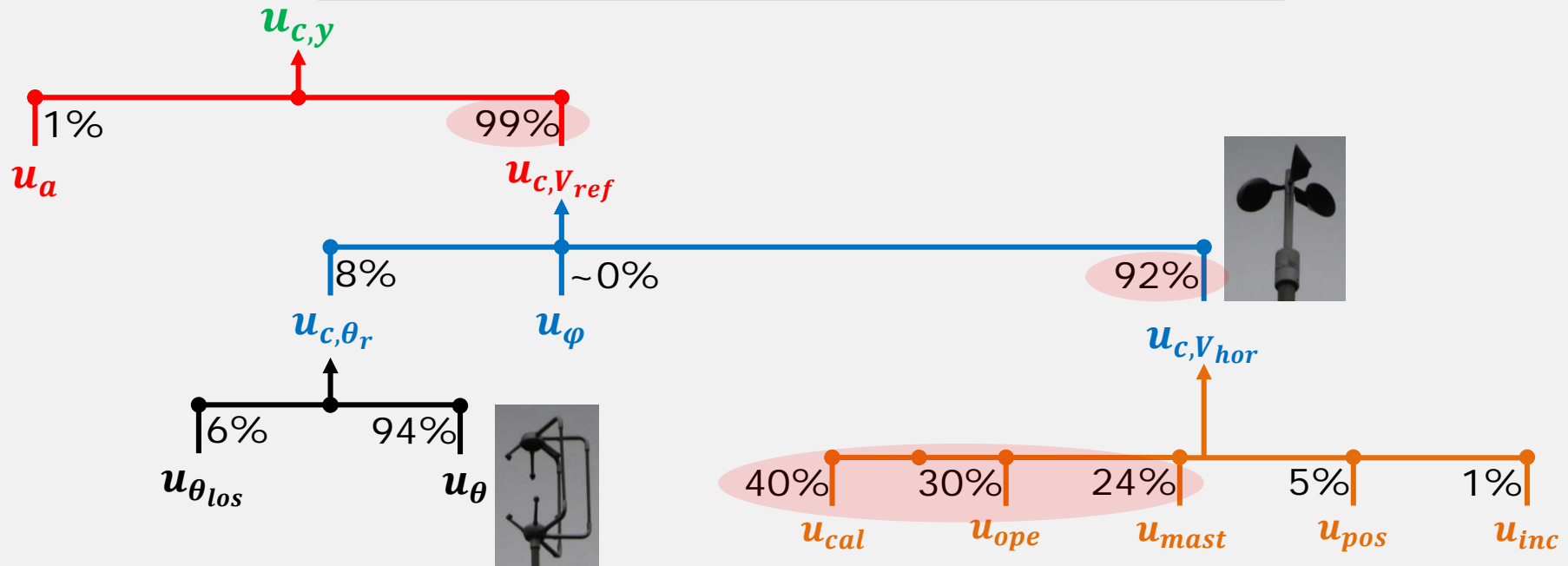
Bottom LOS



Uncertainty of LOS velocity

Prevailing sources

$$a \cdot V_{\text{ref}} = y = a \cdot V_{\text{hor}} \cdot \cos \varphi \cdot \underbrace{\cos(\theta - \text{LOS}_{\text{dir}})}_{\theta_r}$$




• Conclusions:

- the lidar V_{los} uncertainty is almost entirely inherited from the cup
- need to improve uncertainty assessment of cup anemometers
- OR
- need for new reference sensors

Take-aways

- **Calibration of nacelle lidars at DTU**

- the white-box methodology is now 
 - a well-proven method
 - the preferred technique by industry
- Procedures available for different types of commercial systems

- **The barriers, what we need:**

1. better reference anemometers: move away from cups? (their uncertainty prevail massively)
2. shorter calibration procedures: especially true for pulsed syst.
3. unify methods and improve measurement setups
4. work on the propagation of lidar V_{los} uncertainty to reconstructed wind field characteristics
5. And... maybe dig into what's upstream V_{los} !
(estimators, ranging, time stability of optics, etc)

Thanks for your attention!



Scientific article:
Remote Sensing of wind energy



remote sensing



Article

Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

Antoine Borraccino ^{*,†}, Michael Courtney [†] and Rozenn Wagner [†]

Example reports

DTU E-0087

DTU E-0088

More info:

- website www.unitte.dk
- contact:
borr@dtu.dk, mike@dtu.dk

Preparing for questions - Calibration of wind lidars

Power performance testing

The modern ways (2/2)

Remote sensing instruments

—

Future/Now: use of **nacelle-based wind lidars**



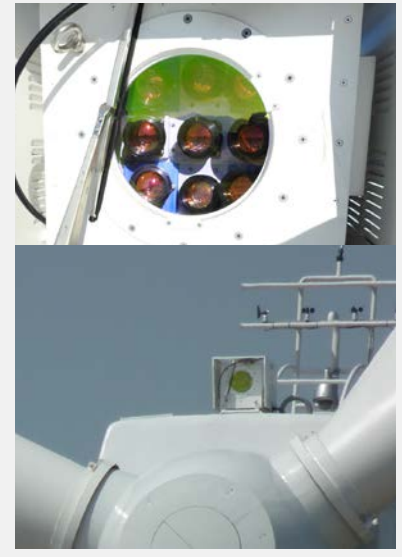
ZephIR Dual Mode
(scanning)
by *ZephIRLidar*



Wind Iris
(4-beam)
by *AventLidar*



Wind Eye
(4-beam)
by *Windar Photonics*



Diabrezza
(9-beam)
by *Mitsubishi Electric*



Publications

- **Publications:**

- DTU E-0086 report → generic methodology
- DTU E-0087 report → detailed procedure 5B-demo
- DTU E-0088 report → detailed procedure ZDM
- Journal paper
 - *Remote Sensing of Wind Energy* (special issue)
 - methodology, results, discussions, 2-beam example
 - doi: 10.3390/rs8110907



remote sensing

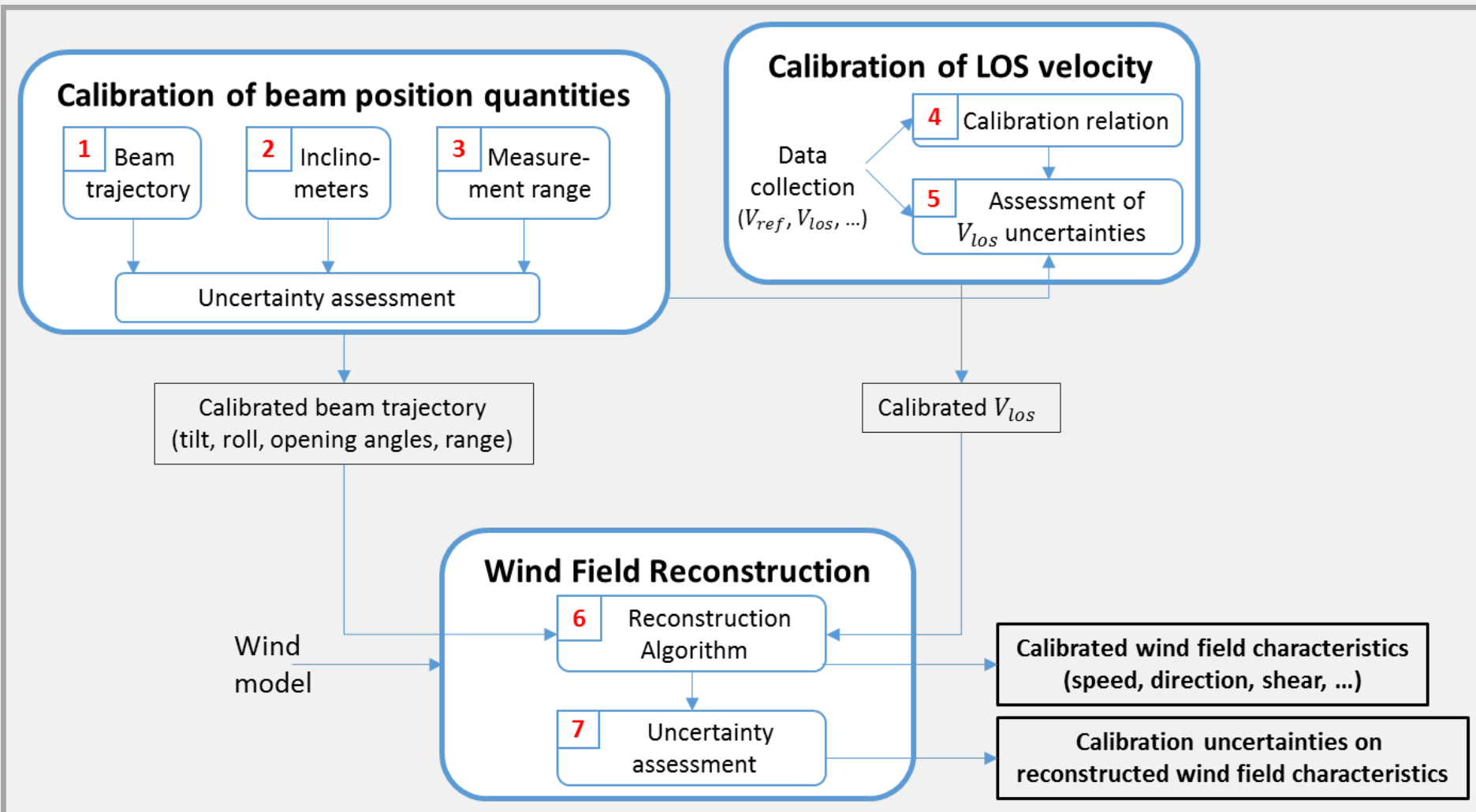


Article

Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

Antoine Borraccino ^{*,†}, Michael Courtney [†] and Rozenn Wagner [†]

Calibration of wind lidars: white-box methodology



Calibration of wind lidars: white vs. black-box methodology (1/2)

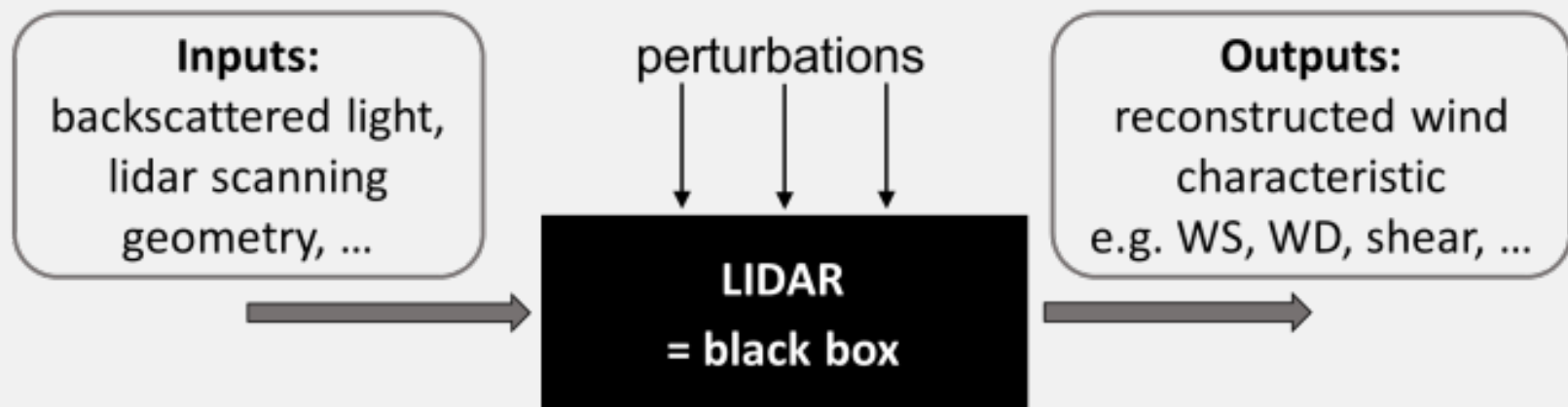
- **Black-box**

- Direct comparison of reconstructed wind parameters

PROS: simple, limited knowledge required

CONS: lidar-specific, practical setup unrealistic, and ...

➔ It simply does not work for nacelle lidars!



Generic calibration methodology

1) beam positioning quantities

• Step 1: calibration of beam positioning quantities

- inclinometers (tilt, roll)
- lidar geometry: cone or opening angles

➔ Procedures are lidar-specific

➔ We used hard target methods to detect beam position



2) Calibration of LOS velocity

Method and data analysis

- **Main data**

- **Cup**: horizontal wind speed V_{hor}

- **Sonic**: wind direction θ

- **Lidar**: LOS velocity V_{los} ; tilt angle φ

Reference quantity

$$V_{ref} = V_{hor} \cos \varphi \cos(\theta - LOS_{dir})$$

- **LOS direction evaluation**

- fit of wind direction response (part 1)

- Residual sum of squares process (part 2)

- **Comparison between**

- Lidar-measured LOS velocity V_{los}

- Reference quantity: pseudo-LOS velocity V_{ref}

- derived from calibrated ref. instruments

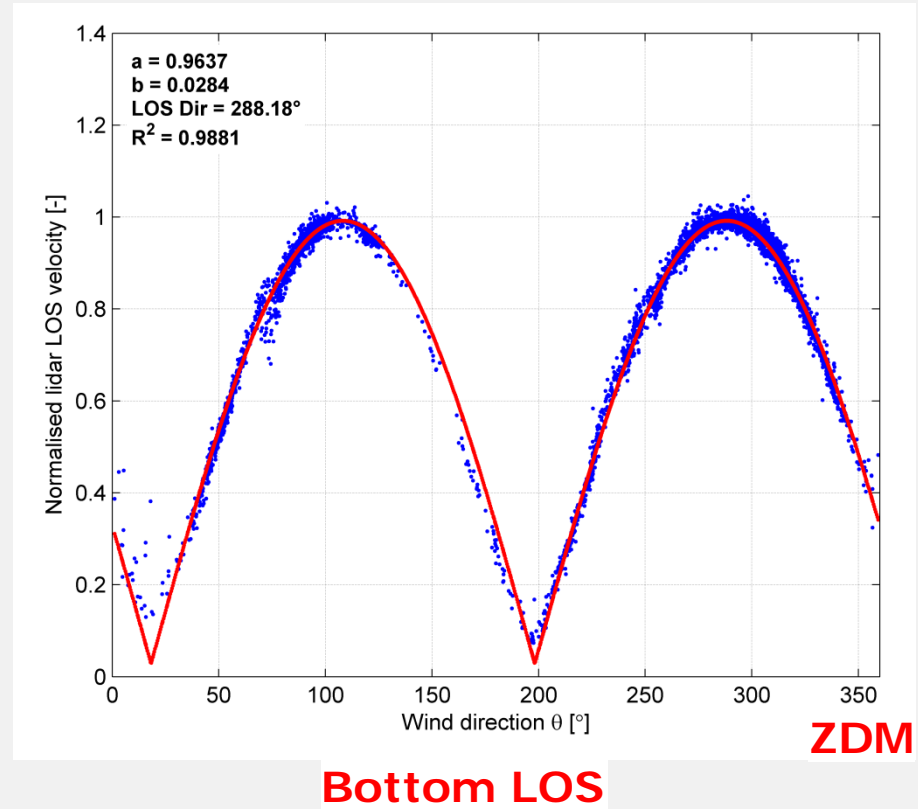
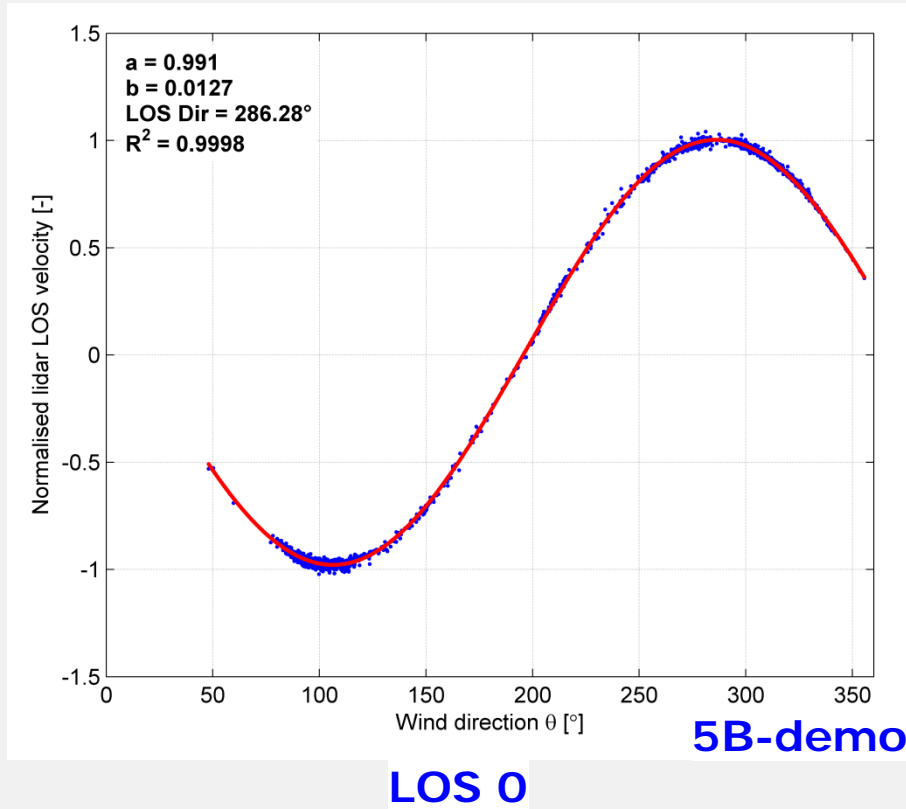


2) Calibration of LOS velocity

Data analysis (1/2)

- **LOS direction evaluation (part 1)**

- Cosine / rectified cosine fitting to wind direction response
- The lidar LOS is normalised by the horizontal speed
- ➔ Gives a first good estimation of LOS direction in sonic CS



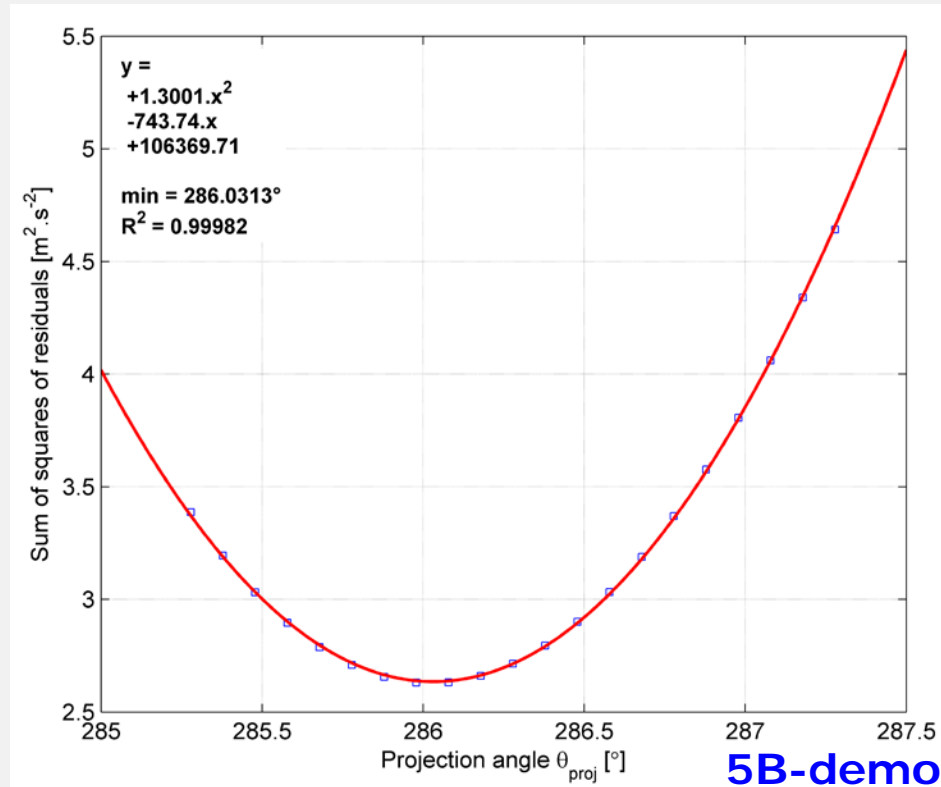


2) Calibration of LOS velocity

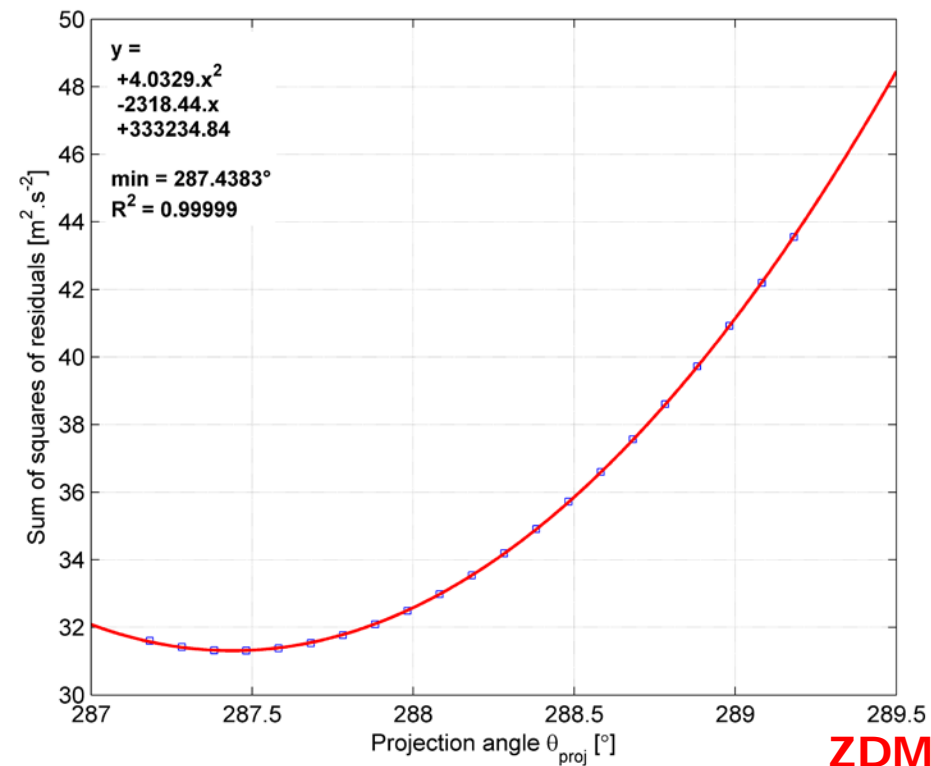
Data analysis (1/2) – RSS process

• LOS direction evaluation (part 2)

- Projection angle range: $\pm 1^\circ$ to cosine fitted LOS_dir
- Linear reg. each 0.1°
- **LOS dir = min parabola**



LOS 0



Bottom LOS



Calibration results

- **Summary:**

- lidar-measured LOS velocity: error of $\sim 0.5 - 0.9\%$
- excellent agreement with the reference quantity V_{ref} : $R^2 > 0.9998$
- LOS direction method provides robust results ($\pm 0.05^\circ$)

Lidar	LOS	Calibration relation			
		θ_{los}	a	R^2	N_{pts}
5B	LOS 0	286.03°	1.0058	0.9999	742
	LOS 1	285.99°	1.0072	0.9999	502
	LOS 2	285.99°	1.0084	1.0000	1087
	LOS 3	286.06°	1.0090	0.9999	446
	LOS 4	285.99°	1.0059	1.0000	1508
ZDM	$179^\circ - 181^\circ$ azimuth	287.44°	1.0050	0.9998	2140

Uncertainty assessment: how to combine components?

- **GUM methodology**: analytic method

- 1) Define measurement model: $y_m = f(x_1, x_2, \dots, x_n)$

- 2) Law of propagation of uncertainties:

$$U_c = \sqrt{\sum_{i=1}^n \left(\frac{\partial y_m}{\partial x_i} \cdot u_{x_i} \right)^2} \text{ for uncorrelated inputs } x_i$$

- 3) Expanded uncertainty with coverage factor k

$$U_{exp} = k \cdot U_c$$

typically, k=2 corresponds to 95% confidence interval

What are the uncertainty sources?

• Reference instruments uncertainties

– HWS (IEC 61400-12 procedure for cups)

- Wind tunnel calibration uncertainty

$$u_{cal} = u_{cal\ 1} + \frac{0.01}{\sqrt{3}} \cdot \langle HWS \rangle$$

- Operational uncertainty

$$u_{ope} = \frac{1}{\sqrt{3}} \cdot \text{cup class number} \cdot (0.05 + 0.005 \cdot \langle HWS \rangle)$$

- Mounting uncertainty

$$u_{mast} = 0.5\% \cdot \langle HWS \rangle$$

– Wind direction, from calibration certificate of sonic anemometer:

$$u_{WD} \approx 0.4^\circ$$

What are the uncertainty sources?

- **Calibration process uncertainties**

- LOS direction uncertainty

$$u_{LOS\ dir} = 0.1^\circ$$

- Uncertainty of tilt inclination angle

$$u_\varphi = 0.05^\circ$$

- Beam positioning uncertainty: $u_H = 10\ cm$, shear $\alpha_{exp} = 0.2$

$$u_{pos} = \alpha_{exp} \cdot \frac{u_H}{H} \cdot \langle HWS \rangle \approx 0.23\% \cdot \langle HWS \rangle$$

- Inclined beam and range uncertainty

$$u_{inc} = 0.052\% \cdot \langle HWS \rangle$$

"how the probe volume affects the RWS estimation when the beam is inclined"
(see model in DTU report E-0086, Annex A)